Keck II Mid-Infrared Imaging of the Young Stellar Object WL16

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ABSTRACT

WL16 is unique among the members of the young, forming star cluster embedded in the nearby ρ Oph cloud core in exhibiting an extended, high surface brightness disk in the emission features originating from solid-state aromatic hydrocarbons. Here, we present diffraction-limited, mid-infrared (7.7–24.5 μm) images of the extended, $\sim$ 900 AU diameter dust disk surrounding this young stellar object acquired at the Keck II telescope. Our new determination of the source's bolometric luminosity, $\sim$ 7 $L_\odot$, at a distance of 125 pc, used HIRES-processed images of the IRAS data. This luminosity corresponds to that of a 1.5 $M_\odot$ ZAMS star. By modeling the spectral energy distribution of the inner disk component, we derive $A_V \sim 28$ through the cloud to the source, consistent with WL16 being embedded halfway through the cloud along our line-of-sight.

The disk emission, which is visible at all mid-infrared wavelengths, is dominated by very small grains (VSG's) and polycyclic aromatic hydrocarbons (PAH's). We find the disk to be inclined 62.2 $\pm$ 0.4 degrees to our line-of-sight, with its major axis at position angle 70$\pm$ 2 degrees. The disk emission is optically thin, consistent with the upper limit on the disk mass of $\leq$ 0.0015 $M_\odot$ set by millimeter continuum observations. Although the surface brightness of the disk emission is remarkably symmetrical at radii exceeding $\sim$ 300 AU ($2\farcs5$), we find an asymmetry in the disk's surface brightness at all wavelengths for 125 AU $\leq$ r $\leq$ 300 pc ($1''$–$2\farcs5$). The explanation of this asymmetry in terms of disk clearing or the presence of planetary bodies awaits careful numerical simulations tailored specifically for this source.

Subject headings: circumstellar matter—dust, extinction—infrared:ISM: lines and bands—stars:formation—stars:individual(WL16)—stars:pre-main-sequence

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1. Introduction

WL16, invisible at optical wavelengths, was first discovered via near-infrared photometry (Wilking & Lada 1983) as a member of the deeply embedded cluster currently forming in the highest extinction core of the nearby ρ Ophiuchi cloud (Barsony et al. 1997 & references therein). At first, WL16 was thought to be a few $\times$ 10^5 yr old star+disk system embedded in a remnant infall envelope (Lada 1987, Adams, Lada, & Shu 1987, Wilking, Lada, & Young 1989). However, the declining spectral slope between 4.8–20 μm found by smaller aperture (6″–8″) ground-based mid-infrared photometry along with the sensitive upper limit to its millimeter continuum flux argues for a more evolved, $\sim$ a few $\times$ 10^6 yr old star+disk system (André & Montmerle 1994, Greene et al. 1994, Casanova et al. 1995, Motte et al. 1998).

The mass of the central young stellar object (YSO) in WL16 is within the range $1.4\ M_\odot \leq M \leq 2.5\ M_\odot$, based on kinematic considerations, (Dent & Geballe 1991, Carr et al. 1993, Chandler et al. 1993, Chandler et al. 1995). The inner disk (3–30 $R_\odot$) around WL16 has been modeled as having a high inclination angle (> 48°) with an accretion rate from the disk to the star of $\dot{M} \sim 2 \times 10^{-7}$ $M_\odot$ yr^{-1} (Najita et al. 1996a). Whereas the inner disk properties were derived from near-infrared spectroscopy of the CO molecule, velocity-resolved spectroscopy of the Brγ hydrogen line toward WL16 reveals independent evidence for the presence of infalling gas at spatial scales smaller than that of the inner disk radius (Najita, Carr, & Tokunaga 1996b, Hartmann, Hewett, & Calvet 1994).

Young stellar objects of intermediate mass ($2 \leq M \leq 8\ M_\odot$) are known as Herbig AeBe stars (Herbig 1994), and are relatively rare. Just a half dozen of the 100-200 member young stellar population of the ρ Oph cluster falls into this category (Greene et al. 1994). A substantial fraction, though not all, of HAeBe stars are found to emit in the well-known, solid-state spectral features: the C–H bond resonances at 3.3 μm, 8.6 μm, 11.3 μm, and 12.7 μm, and the C–C bond stretches at 6.2 μm and 7.7 μm (*e.g.*, Tokunaga et al. 1991, Brooke, Tokunaga, & Strom 1993, Hanner, Brooke, & Tokunaga 1995). ISO observations have confirmed the presence of PAH emission in many HAeBe stars (Waters & Waelkens 1998). It has been suggested that the presence or absence of these features may be due to an excitation effect, since the PAH band strengths seem to increase with earlier spectral type (Wooden 1994).

WL16 exhibits the entire suite of PAH emission features (Hanner et al. 1992, Deutsch et al. 1995, Natta & Krügel 1995). Previous mid-infrared imaging of WL16 has revealed the presence of extended, elliptically-shaped emission of $\sim$ 8″ extent along its major axis (Deutsch et al. 1995, Emerson et al. 1996, Moore et al. 1998). Spatially-resolved mid-infrared spectroscopy of this elongated dust structure has confirmed the presence of both very small grains (VSG's) and aromatic hydrocarbons (or PAH's) throughout (DeVito & Hayward 1998).

In order to shed further light on both the central object and its surrounding disk, we have imaged WL16 at unprecedentedly high spatial resolution ($\sim$ 0.″3) on the Keck II 10-meter telescope. We have also re-processed the available *IRAS* data with the HIRES algorithm (Aumann, Fowler, & Melnyk 1990), which provides an order of magnitude improvement in spatial resolution over the previously available Survey Co-ADD data, to redetermine WL16's bolometric luminosity.

2. Observations

We observed WL16 with JPL's mid-infrared camera, MIRLIN (Ressler et al. 1994), at the visitor port of the Keck II telescope on UT 14 March 1998 and 27 January 1999. The sky was clear and dry on both nights ($\tau_{225GHz} \sim 0.06$ and ~ 0.04, respectively). MIRLIN employs a Boeing HF–16, 128×128 pixel, Si:As impurity band conductor detector array, and, with the f/40 chopping secondary mirror at Keck II, has a plate scale of 0.″138 per pixel (17.″5 field-of-view).

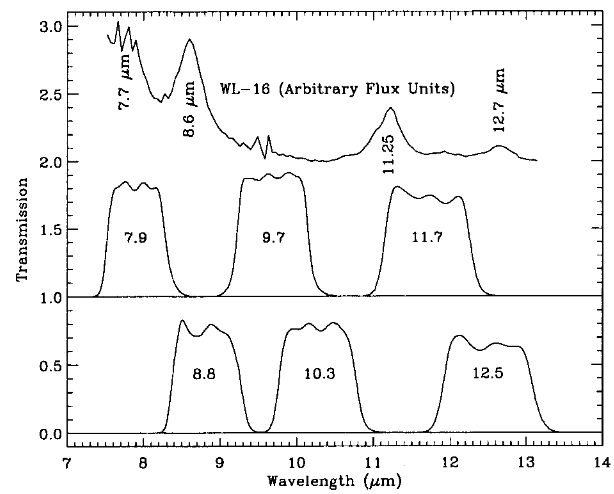

Fig. 1.— MIRLIN filter transmission curves along with a continuum-subtracted spectrum of WL16 (DeVito & Hayward, 1998). The filter curves are reproduced from the manufacturer's data taken at 77 K. The filters at 7.9, 9.7, and 11.7 μm have had their baselines shifted by one for clarity. The 9.7 and 10.3 μm filters sample the "continuum" reasonably cleanly, while the other four filters each sample a PAH feature.

Background subtraction was performed by chopping the telescope secondary mirror 8″ in a north-south direction, then nodding the entire telescope 30″ east-west, completely off the source, in order to remove residual differences. Observations were performed through the six 10 μm "silicate" filters and the 17.9 μm filter on 14

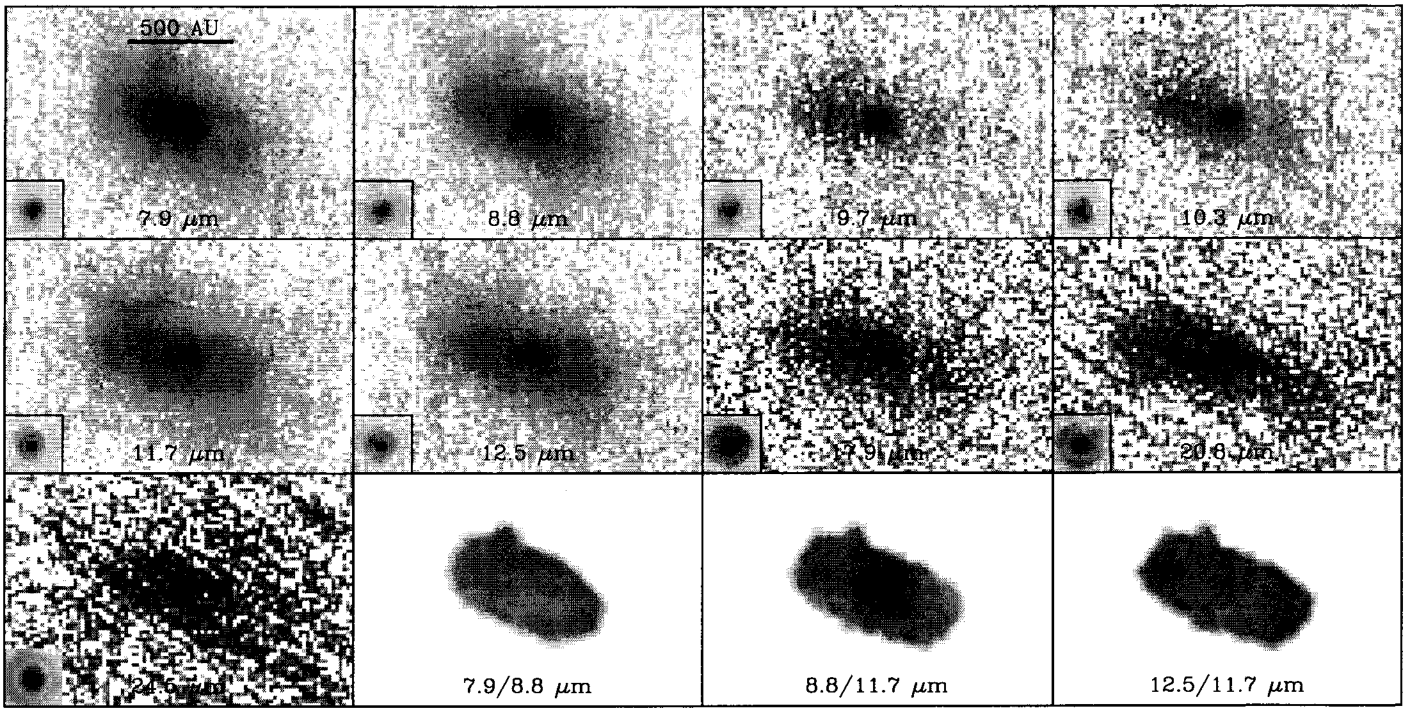

Fig. 2.— Images of WL16 at all observed wavelengths and color ratios for selected wavelength pairs. North is up, east is left for all mages, and the images have been scaled from zero flux to the maximum pixel value, then raised to the 0.4 power to compress the dynamic range. The pixel scale is 0.138 arcsec/pix, giving the frames a roughly 13×9 arcsecond field of view. The PSF calibrator (β Leo at $\lambda < 13$ microns, α Hya at the longer wavelengths) is shown in the lower left corner of each frame. A distinct point source is visible in all images with $\lambda > 9$ μm. The ratio images are surprisingly uniform; there are no significant color gradients contained in any pair of images (including those not displayed here), with the exception of the ~ 1.5 arcsecond diameter "core" in the 7.9 and 8.8 μm images.

March, and through the 20.8 μm and 24.5 μm filters on 27 January. All of these filters have a passband of $\Delta\lambda/\lambda \approx 10\%$, except for $\Delta\lambda/\lambda \approx 3\%$ at 24.5 μm. Plots of the six 10 μm filter passbands are shown in Figure 1, along with the continuum-subtracted mid-infrared spectrum of WL16 (DeVito & Hayward 1998), to indicate how the PAH emission features were sampled.

Total on-source integration time through each of the "silicate" filters was approximately 30 seconds—200 coadded chop pairs of roughly 80 msec duration in each of the two beams. Total on-source integration times through the longer wavelength filters were 2.0, 2.7, and 2.4 minutes through the 17.9, 20.8, and 24.5 μm filters, respectively. The primary photometric standard and point spread function calibrator was the A3V star, β Leo, which has a magnitude ranging from 1.91 to 1.84 from 7–13 μm. The calibrator at 17.9 and 20.8 μm was α Hya, a K3III star with a magnitude of -1.49; the standard at 24.5 μm was β Lib, a 2.84 magnitude B8V star. Consistency checks were performed with α CMa (mag = -1.39) and σ Sco (mag ~ 2.40); the latter proved to be an easily-resolved binary with 0.45 arcsecond separation. Atmospheric extinction was corrected by observing the calibrators at several different airmasses. The resulting coefficients were found to be quite low (< 0.1–0.2 magnitudes per airmass).

3. Results and Discussion

Figure 2 shows the mid-infrared images of WL16 at nine different wavelengths. Somewhat surprisingly, the disk is easily visible at all wavelengths, including those in the PAH "continuum", though it is certainly brightest in the PAH emission features. This suggests that the disk is composed of several constituents; Malfait et al. 1998 found that the mid-infrared emission spectrum of the Herbig Ae/Be star HD 100546 could be well fit by a mixture of PAHs, amorphous silicates, FeO, and forsterite (Mg_2SiO_4). It is plausible that WL16's disk is composed of similar materials, with emission from FeO and/or forsterite dominating in the 20 μm region where there is little PAH emission.

The disk extent derived from these images is 7×3.5 arcseconds, corresponding to 875 × 440 AU at the source for d = 125 pc (de Geus, de Zeeuw, & Lub 1989, de Geus 1992). The position angle of the disk's major axis, measured east from north, is 70±2 degrees. The minor-to-major axis ratio is found to be 0.466±0.007, yielding an inclination angle of 62.2±0.4 degrees of the disk to our line-of-sight if we assume the disk to be intrinsically circular and to appear elongated only because of geometry effects. This value is high, but within the limits ($48° \leq i \leq 65°$) deduced for the inclination angle of the inner disk from kinematical modeling of the CO emission (Dent & Geballe 1991, Carr et al. 1993, Chandler et al. 1993, Chandler et al. 1995). The corresponding mass limits for the central YSO are 1.4 $M_\odot \leq M \leq 2.5$ $M_\odot$. Our direct determination of the disk's inclination angle provides a firmer constraint on the central object's mass and evolutionary status than had been available previously. Since the lower mass limit, 1.4 $M_\odot$, is obtained for $i = 65°$, our measurements of the disk's inclination angle argue for an older, lower mass system within the range of possibilities evaluated by Carr et al. (1993).

We present new mid-infrared and far-infrared photometry for WL16 in Table 1. To compare our photometry with previous ground-based results (e.g., Lada & Wilking, 1984, Moore et al. 1998), we have performed false aperture photometry with an 8″ software aperture. As can be seen from Table 1, our values agree with previous measurements to within the errors (our random errors are about 3% at 8–13 μm, 7% at 17.9 and 20.8 μm, and 30% at 24.5 μm). The good agreement between the data sets indicates that WL16 is not highly variable. By integrating under the entire spectral energy distribution plotted in Figure 3, we arrive at a bolometric luminosity of $\sim$ 7 $L_\odot$ for an assumed distance of 125 pc, in good agreement with the previous determination of 10 $L_\odot$ for d = 160 pc derived from *IRAS* pointed observations (Young, Lada, & Wilking 1986). Again, this rather low luminosity argues for WL16 being a lower mass, older system within the range of possibilities evaluated by Carr et al. (1993).

In order to arrive at an independent estimate of the extinction through the cloud to WL16, we have performed photometry using point-spread-function (PSF) fits, with a reference star as the kernel. We assume this fit will be dominated by flux from the star and hot inner disk, and will have negligible contamination from the emission from the nebula. The resulting derived fluxes are listed in Table 1 and are plotted in Figure 3.

By assuming the central, unresolved source to be a star plus geometrically thin disk system such as those modeled by Adams, Lada, & Shu 1987, and that the wavelength-dependent extinction follows a Draine & Lee 1984 extinction law, we can reproduce the observed silicate feature (9.7 μm) optical depth and the spectral energy distribution (SED) shape very well for an $A_V = 28$ foreground screen and an 8000 K stellar source if we modify the ALS model so that the disk becomes optically thin at wavelengths $\gtrsim 10$ μm. We therefore assume an $A_V = 28$ and deredden the PSF-fit fluxes and plot them in Figure 3; the fit model is also plotted as the solid line. Two alternative fits are shown for comparison: a 2000 K blackbody, which we cannot rule out as

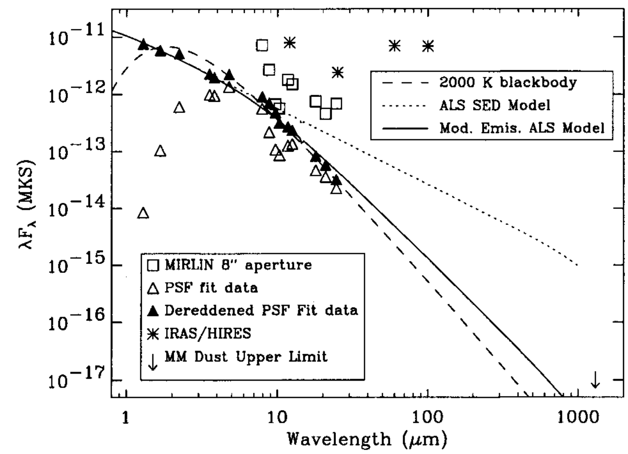

Fig. 3.— The spectral energy distribution of WL16. The raw data points are indicated with open symbols: triangles represent the values of point-spread-function fits; squares represent integrations over an 8″ aperture in the mid-infrared (the aperture values in the near-infrared do not differ from the PSF fits, since WL16 appears unresolved at these wavelengths). The HIRES-processed IRAS values are shown as stars; the 1.3 mm upper limit is indicated by the arrow. The dereddened ($A_V = 28$) PSF-fit data are indicated with solid triangles. The best fitting model, that of a star+optically-thin-disk, is plotted as the solid line. A pure ALS model is shown as a dotted line; this model is ruled out because of the overprediction in the far-infrared and millimeter. A 2000 K blackbody is plotted (dashed line) for reference and may represent an averaged, optically thick "surface" in the star+disk system.

a possibility, though it likely represents the temperature of the surface where the star+disk appears to be optically thick, and a pure, optically thick, ALS model. This model clearly overpredicts the mid-infrared and millimeter fluxes, thus the star+optically-thin-disk system provides the most satisfying fit to the dereddened data for the central, unresolved source.

The de-reddened SED is very smooth (Figure 3) and the disk shows a remarkable lack of color gradients, as demonstrated by the wavelength independence of the spatial distribution of the disk emission (see Figures 2 and 4). We conclude the entire WL16 system must be buried in the cloud core behind an $A_V = 28$ screen of foreground material, since the line of sight beam-averaged (55″ FWHM) extinction throughout the entire cloud in the direction of WL16 is estimated at $A_V = 70$ mag with a 50% error from $C^{18}O$ observations (Wilking 1998).

Figure 4 shows linear cuts of intensity as a function of angular separation from the central source along the disk's major axis for each of the wavelengths we ob-

TABLE 1
PHOTOMETRY OF WL16

Wavelength λ_0 (μm)	PSF Fitting Flux (Jy)	Aperture Photometry Flux[a] (Jy)	Previously Published Flux (Jy)	References
1.2	0.0037	...	0.0040	(1,2)
1.65	0.059	...	0.071	(1,2)
2.2	0.45	...	0.48	(1,2)
3.4	1.17	...	1.36	(1,2)
3.8	1.22	...	...	(1)
4.8	2.18	...	2.02	(1,3)
7.9	1.49	19.13	...	...
8.8	0.65	7.89	8.3	(3)
9.7	0.35	2.18	1.6	(3)
10.3	0.30	1.97	1.8	(3)
11.7	0.49	7.07	7.1	(3)
12	...	16.0 (HIRES)	18.8	(4)
12.5	0.57	6.30	6.25	(3)
17.9	0.28	4.53	...	...
20.8	0.25	3.19	4.8[b]	(3)
24.5	0.19	5.67	...	...
25	...	14.4 (HIRES)	<40	(4)
60	...	129 (HIRES)	202	(4)
100	...	223 (HIRES)	...	(4)
1300	...	...	<0.006	(5)

[a]All quoted fluxes are for an 8″ diameter aperture, except for HIRES fluxes which were determined from a 45″ diameter aperture after local background subtraction.

[b]Broadband Q measurement—$\Delta\lambda/\lambda \sim 40\%$

REFERENCES.—(1) Ressler (1992), (2) Wilking & Lada (1983), (3) Lada & Wilking (1984), (4) Young, Lada, & Wilking (1986), (5) Motte, André, & Neri (1998)

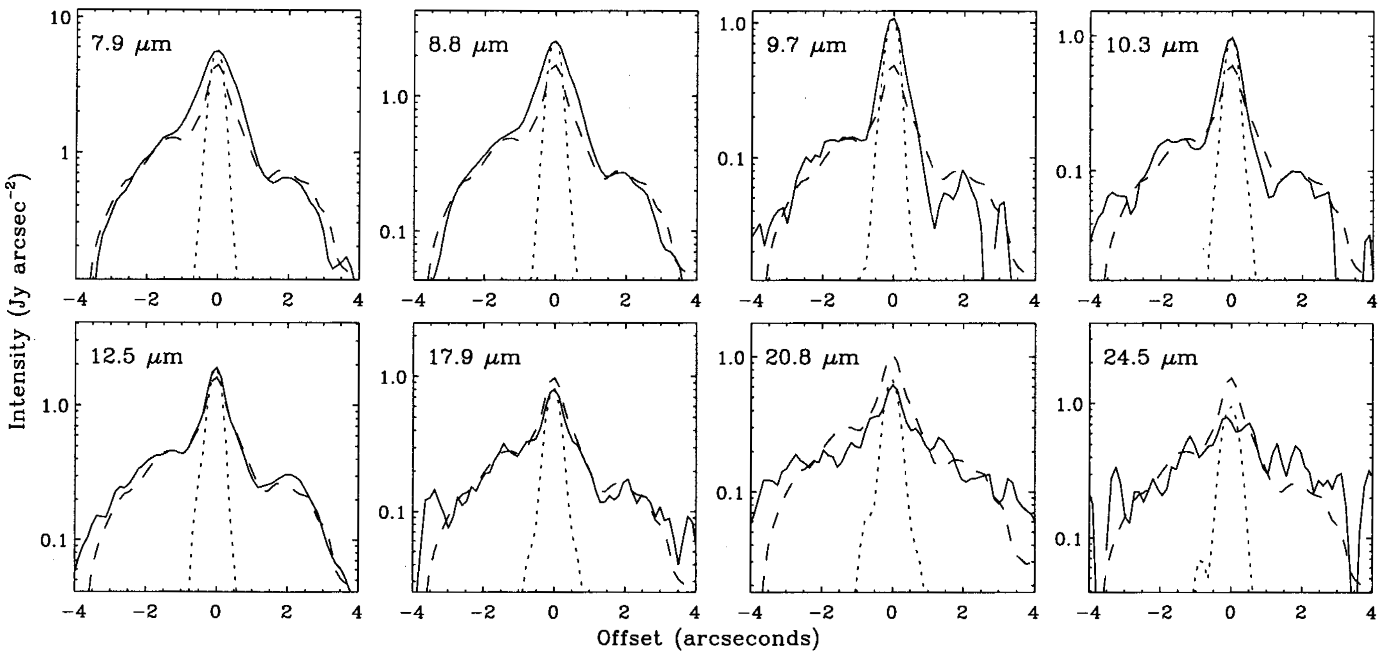

Fig. 4.— Line cuts along the disk's major axis at all observed wavelengths. In each panel, the solid curve is the intensity profile at the indicated wavelength, the dotted curve is the PSF profile at that wavelength, and the dashed curve is the scaled profile at 11.7 μm. In spite of the differing central source intensities and the presence of additional emission within the central 1.″5 at the two shortest wavelengths, the disk's intensity profile is essentially identical at all wavelengths, including at 17.9–24.5 μm, where no PAH emission should be present. Note the disk's asymmetry at angular distances 1.″0–2.″5, also apparent at all wavelengths.

served, all referred to the 11.7 μm data and their respective PSFs. The disk's surface brightness is higher in the filters encompassing the aromatic hydrocarbon emission features than in those which do not. However, the spatial distribution of the emission is remarkably similar to the 11.7 μm distribution in all of the filters. (This also holds true in the fully two-dimensional case, where ratios of any pair of images are very flat; three examples are shown in Figure 2.) This phenomenon can be explained by the presence of very small grains (VSG's) present throughout the disk of WL16, as has been noted previously (Natta & Krügel 1995, DeVito & Hayward 1998, Moore et al. 1998). The bright, somewhat resolved ($d \sim$ 1.″5 core in the shorter wavelength (7.9 and 8.8 μm) plots of Figure 4 does not appear in the longer wavelength ($\geq$ 9 μm) cuts, confirming the previously inferred color gradients attributed to excitation/ionization of the PAH's that are located closer in towards the central, illuminating source (DeVito & Hayward 1998). Finally, the intensity profiles along the disk's major axis show an asymmetry at angular separations between 1″–2.″5, corresponding to radii, 125 AU $\leq$ r $\leq$ 300 AU. This asymmetry could be due either to an enhancement in the column density of emitters or an enhancement in the number of exciting photons at these locations. The possibility of the presence of giant planets or disk gaps to account for this asymmetry, observed at all wavelengths, awaits further detailed modeling for the specific parameters relevant to this source (e.g., Lecavelier des Etangs et al. 1996 and references therein).

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REFERENCES

Adams, F.C., Lada, C.J., & Shu, F.H. 1987, ApJ, 312, 788

André, Ph. & Montmerle, T. 1994, ApJ, 420, 837

Aumann, H. H., Fowler, J., & Melnyk, M. 1990, AJ, 99, 1674

Barsony, M., Kenyon, S.J., Lada, E.A., Teuben, P.J. 1997, ApJS, 112, 109

Brooke, T. Y., Tokunaga, A. T., & Strom, S. E. 1993, AJ, 106, 656

Carr, J. S., Tokunaga, A. T., Najita, J., Shu, F. H., and Glassgold, A. E. 1993, ApJL, 411, L37

Casanova, S., Montmerle, T., Feigelson, E. D., & André, Ph. 1995, ApJ, 439, 752

Chandler, C. J., Carlstrom, J.E., Scoville, N.Z., Dent, W.R.F., & Geballe, T. R. 1993, ApJL, 412, L71

Chandler, C. J., Carlstrom, J. E., and Scoville, N. Z. 1995, ApJ, 446, 793

de Geus, E., de Zeeuw, P., & Lub, J. 1989, A& A, 216, 44

de Geus, E. 1992, A& A, 262, 258

Dent, W.R.F. & Geballe, T.R. 1991, A & A, 252, 775

Deutsch, L. K., Hora, J. L., Butner, H. M., Hoffman, W. F., and Fazio, G. G. 1995, Ap&SS, 224, 89

DeVito, B. and Hayward, T. L. 1998, ApJL, 504, L43

Draine, B. T. and Lee, H. M. 1984, ApJ, 285, 89

Emerson, J. P., Moore, T. J. T., Skinner, C. J., and Meixner, M. M. 1996, in The Role of Dust in the Formation of Stars, Käufl and Siebenmorgen eds, ESO Astrophysics Symposia, Springer Verlag:Heidelberg, p. 23

Greene, T. P., Wilking, B. A., André, Ph., Young, E. T., & Lada, C. J. 1994, ApJ, 434, 614

Hanner, M. S., Tokunaga, A. T., and Geballe, T. R. 1992, ApJL, 395, L111

Hanner, M. S., Brooke, T. Y., & Tokunaga, A. T. 1995, ApJ, 438, 250

Hartmann, L., Hewett, R., & Calvet, N. 1994, ApJ, 426, 669

Herbig, G.H. 1994, in *The Nature and Evolutionary Status of Herbig Ae/Be Stars*, ASP Conf. Ser. 62, eds. Thé, P.S., Perez, M.R., & van den Heuvel, P.J., p. 3

Hillenbrand, L.A., Strom, S.E., Vrba, F.J., & Keene, J. 1992, ApJ, 397, 613

Lada, C. J. 1987 in Star Forming Regions, eds. M. Peimbert & J. Jugaku (Doredrecht: Reidel), p.1

Lada, C. J. & Wilking, B. A. 1984, ApJ, 287, 610

Lecavelier des Etangs, A., Scholl, H., Roques, F., Sicardy, B., & Vidal-Madjar, A. 1996, Icarus, 123, 168

Malfait, K., Waelkens, C., Waters, L. B. F. M., Vandenbussche, B., Huygen, E., & de Graauw, M. S., 1998, A&A, 332, L25

Moore, T.J.T., Emerson, J.P., Skinner, C.J., Meixner, M.M., Arens, J.F., & Jernigan, J.G. 1998, MNRAS, 299, 1209

Motte, F., André, Ph., & Neri, R. 1998, ApJ, 439, 752

Najita, J., Carr, J. S., Glassgold, A. E., Shu, F. H., and Tokunaga, A. T. 1996a, ApJ, 462, 919

Najita, J., Carr, J.S., & Tokunaga, A.T. 1996b, ApJ, 456, 292

Natta, A. & Krügel, E. 1995, A&A, 302, 849

Ressler, M. E., 1992, PhD Dissertation, U. Hawaii

Ressler, M. E., Werner, M. W., Van Cleve, J., and Chou, H. A. 1994, Exp. Astr., 3, 277.

Tokunaga, A. T., Sellgren, K., Smith, R. G., Nagata, T., Sakata, T., Nakada, Y. 1991, ApJ, 380, 452

Waters, L.B.F.M. & Waelkens, C. 1998, ARAA, 36, 233

Wilking, B. A. & Lada, C. J. 1983, ApJ, 274, 698

Wilking, B. A., Lada, C. J., & Young, E. T. 1989, ApJ, 340, 823

Wilking, B.A. 1998, priv. comm.

Wooden, D.H. 1994, in *The Nature and Evolutionary Status of Herbig Ae/Be Stars*, ASP Conf. Ser. 62, eds. Thé, P.S., Perez, M.R., & van den Heuvel, P.J., p.138

Young, E.T., Lada, C.J., & Wilking, B.A. 1986, ApJL, 304, L45

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